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Quantifying the sensation of temperature: A new method for evaluating the thermal behaviour of building materials

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ABSTRACT

When touched, dissimilar materials, such as metal and wood, evoke different thermal sensations when both are maintained at room temperature due to the inherent differences in their thermo-physical properties. In this study, we employed psychophysical experiments to quantify the tactile perception of surface temperature using pine wood, oak wood and ceramic floor tile. Twenty-four participants (10 female, 14 male; age 27+- 5 years) took part in the experiment. The results showed that a pine surface at 20.0 ºC feels equally cold to that of an oak surface with a temperature of 20.9 ºC. After increasing or decreasing the oak surface temperature by 1.2 °C (from 20.9 °C) it began to feel, respectively, either warmer or colder than the pine surface at 20 °C. Similarly, the pine surface at 20.0 °C and ceramic tile surface at 22.8 °C evoked an equal sensation of cold and, by raising the temperature of the ceramic tile by 0.9 °C from 22.8 °C, it began to feel warmer than the pine at 20 °C. On the other hand, by decreasing the temperature of the ceramic tile by the same amount (0.9 °C), the pine surface at 20 °C began to feel warmer. The quantification of temperature perception seems to offer a promising approach to precisely evaluating the tactile warmth and thermal behaviour of building materials used in diverse applications. We further discuss how these results might offer insights into how the heating/cooling energy required in buildings might be reduced with the careful selection of construction materials.

1. Introduction

The tactile warmth of materials, which describes how cold or warm they feel to the touch [1], is considered an important characteristic for users when selecting materials in office and home environments [26]. The physical thermal properties of materials are the governing factors behind such variations in tactile warmth as well as the thermal behaviour of the materials [20,19]. A material's thermal behaviour explains how it interacts, in a thermal sense, with its surroundings and is determined by its ability to exchange thermal energy with the surrounding air at a nearly constant ambient temperature [9,4]. Both the sensory tactile warmth and thermal behaviour of materials can influence the human thermal experience in living spaces. Therefore, the choice of building materials can determine the thermal experiences of the surroundings, which implies that material selection may influence energy consumption by affecting comfort levels and thus the need for additional space heating or cooling. If, however, we are to exploit this potential to improve the energy efficiency of buildings, we need to try to quantify these subjective perceptions of temperature.

The onset of the temperature perception of a material surface initiates with the heat exchange process that takes place between the skin and the material surface upon contact. A sensation of warmth arises when the stimulus surface temperature ranges between 36 and 43 °C and the skin absorbs the heat. A cold sensation is felt when the surface temperature is from 30 to 16 °C, and the heat is extracted away from the skin to the material surface (see, for review, [24]). Neither cold nor warm sensations arise when the surface being touched is between 30 and 36 °C, near the core body temperature. Temperature sensitivity differs across body regions as well; for instance, hand skin is more sensitive than foot skin for both cold and warm temperatures [8,22] and the sensitivity deteriorates with increasing age [23]. These human temperature sensation profiles can be measured using psychophysical methods. The adoption of the test procedures and equipment in

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Table 1
Thermal properties of test materials.

Material	Density (air dry-fresh)*, ρ (kg/m^3)	Thermal conductivity, κ (W/m K) (oven dry-12% moisture content)*	Specific heat capacity, c (J/kg K)	Thermal effusivity, η (J/m^2 K s$^{1/2)}$
Pine (*Pinus sylvestris* L.)	480–520	0.10–0.13	1685	284–377
Oak (*Quercus robus* L.)	720–760	0.16–0.19	1685	441–493
Ceramic tile	1800–2200	0.6–1.70	850	958–1782

Source: Glass and Zelinka [6]; Wongsriruksa et al. [27]; Pelit et al. [21]; Gracia et al. [7].

psychophysical studies of temperature sensation vary according to the purpose of the study. However, the measurement of the threshold for discriminating the change in temperature of the thermal stimulus is fundamental in all (see, for review, [2]).

The discrimination threshold (DT) for temperature sensation is the smallest difference between two temperatures that a person can accurately detect. It is sometimes also defined as “just noticeable difference” (JND) between two magnitudes of sensory stimuli [17]. The perceived similarity, on the other hand, refers to the fact that the subjective perception of two stimuli are the same and it is termed the point of subjective equality (PSE) in a psychophysical observation. At the PSE for temperature perception, the observer perceives two thermal stimuli as being equal in their coldness or warmth, although their physical stimulus intensities (surface temperatures) are not necessarily the same [5]. In the present study, we utilised these two psychophysical concepts: the PSE and the DT to quantify the temperature perception of the material surfaces upon touch. We selected wood and ceramic tiles as test materials because of their extensive use in indoor spaces and greater chances of exposure to the human touch, thus influencing the feeling of the thermal environment. However, using these types of materials with differing physical properties as thermal stimuli, in thermal touch quantification is an unexplored area and could pose challenges. The main challenge is the regulation of stimulus intensity during experimentation. In temperature threshold testing, the application of a thermal stimulus is specially calibrated, and when applied to the skin site, it can rapidly cool or warm the skin site as needed (e.g., [15]). Such rapid cooling and warming of the skin when using materials such as wood or ceramic tiles as the thermal stimulus, for example, is not possible due to their relatively poor heat conducting capabilities. In this study, we designed a custom-built test setup to address this challenge, where we used multiple stimulus surfaces from the same material with fixed (predefined) surface temperatures. More details on the arrangement of stimulus intensity-calibration will follow later in the methods section. For now, to understand the underlying temperature sensation process while touching these material surfaces, a short review of their heat exchange ability and underlying physical properties is needed.

The heat exchange ability of materials varies and is a function of their thermal properties [4]. Wide variations in thermal properties exist among often poorly conducting building materials, and materials with higher thermal conductivity (κ). Among wood species, thermal conductivity varies and increases with increasing density, moisture content and ambient temperature [6]. On the other hand, the thermal conductivity of ceramic tiles ranges from 0.6 to 1.7 Wm^{-1}K^{-1}, and correlates more with density (porosity) and less with moisture content [7]. Due to the lower conductivity, moderate density (ρ), and specific heat capacity (c), wood surfaces feel relatively less cold to the touch than ceramic tiles at room temperature. In physical measurements, this thermal behaviour is better reflected through the value of thermal effusivity (η) [20,19]. It is a measure of a material’s ability to exchange heat energy with its surroundings and is defined as the square root of the product of thermal conductivity and volumetric heat capacity, $\eta = (\kappa \rho c)^{1/2}$. Wood, which has a lower value of thermal effusivity than ceramic tiles, therefore exchanges heat energy with its surrounding at a slower pace. The same applies when the material is touched; the lower rate of heat exchange with the skin can evoke a lower intensity of cold sensation than its temperature actually warrants, compared with a material of higher thermal effusivity [11]. Therefore, a material with low thermal effusivity is considered better in sensory tactile warmth.

Subjective experiences of the tactile warmth of materials are measured through rating scales and the intuitive judgement of experts [20,27,26]. The engineering evaluation of tactile warmth is conducted through an empirical and theoretical analysis of the heat exchange phenomenon that occurs between the skin and material surface upon contact, using either skin touch with real materials or in a simulated environment [20,19,18]. These theoretical findings on the heat exchange phenomenon are then compared with subjective data, for example, the judgement of panellists about the tactile warmth of materials [20]. Theoretical heat transfer analysis offers an excellent explanation of the physical phenomenon, for example, why the skin-material interface temperature changes immediately after the skin has made contact with the surface and how a change in skin temperature after surface-contact is related to the thermal effusivity of materials [19,18]. However, they cannot fully account for the human aspect of thermal perception. Apart from the profound bias in subjective ratings and intuitive judgments, there is a serious issue with these approaches where subjects touch the material and rate it on its “perceived warmness”. The resting temperature of the skin typically lies within the range of 26 to 35 °C, which is higher than that of the materials encountered in the ambient environment [25]. Therefore, it is the cold sensation and not the warm one that we perceive while touching material surfaces at room temperature. In the quantification of cold temperature sensation, a material that feels less cold to the touch than another at room temperature can be considered to be superior in tactile warmth. Therefore, subjective ratings on the perceived warmness of material-touch measured at room temperature do not account for the importance of any relationship derived between the physical quantity and the tactile warmth of a material.

In the present study, therefore, our aim was to determine numerical differences between the surfaces of two materials with differing thermal properties, when they were perceived as being equal (measured as PSE) or different (measured as DT) to one another in terms of the temperature sensation upon touch. We hypothesised that the pine, having a lower thermal effusivity compared to oak and ceramic tile (Table 1), should feel equally warm when its actual surface temperature is lower than the surface temperatures of oak or ceramic tile surfaces. In the first experiment, pine surfaces were compared with oak surfaces and in the second experiment with ceramic tile surfaces.

2. Methods

2.1. Participants

Twenty-four participants (14 male, 10 female; mean age = 27.56 ± 5.65 years) took part in the experiments. Twelve participants (7 male, 5 female) were randomly assigned to the first session, in which pine and ceramic tile surfaces were compared, and the remaining participants were assigned to the second session, which included natural (untreated) of pine and oak surfaces. Participation was voluntary, and the participants each received a 20 Euro gift voucher as reimbursement. The Aalto University Research Ethics Committee approved the study and written informed consent was obtained before data collection began. The experiments were conducted in accordance with the Declaration of Helsinki.

2.2. Experimental design

The experiment consisted of a custom-built test set-up, where thermal boxes were used to heat the test-surfaces. All the pinewood surfaces were heated to 20 °C and compared, in a series of two separate experiments, with the surfaces of oakwood (series 1) and ceramic tiles (series 2) that were heated to different temperatures. The ceramic tile surfaces were heated to temperatures ranging from 17.6 to 25.8 °C, whereas the oak surfaces were heated to between 16 and 24 °C. The temperature was varied in 11 steps, each of 0.8 °C. We ran pretests with five participants for each comparison pairs to find the correct temperature range for compariing test surfaces so that the discrimination threshold should lie within the selected temperature range. The participants in the pretests were different from the main test, but the procedure adopted in the pretest was the same as used in the main test. A climate-controlled room was used to conduct the experiment, in which the temperature was maintained at 13 ± 0.4 °C. The 2-alternative forced choice (2-AFC) method was used, where subjects had to touch a pair of surfaces simultaneously, in vision-blocked mode and choose the one that felt colder. In this simple binary decision-making process and repeated trials with a stimulus pair of variable surface temperatures, a psychometric function was calculated, which reflects the empirical probability of the participant's choice as a function of stimulus difference [17].

2.2.1. Test surfaces

The surfaces of untreated pine (*Pinus sylvestris* L.) and oak (*Quercus robur* L.) boards, and ceramic tiles (*product ID: LC68, Trendgrey PEI 2 R9 harmaa. Shop:RTV-Yhtyma OY, Helsinki)* having dimensions of 9.8 cm × 9.3 cm × 6 mm (length × breadth × thickness) were prepared for the test surfaces. The wood surfaces were cut from the same wooden board, and the surface texture was matched by abrading the surfaces with 240-grit sandpaper. All the selected wood samples had a similar grain pattern over the touch surfaces, and they were knot-free to minimise textural cues. The test surfaces were stored under normal room conditions for one month to make sure that the wood moisture content reached equilibrium before the test (Fig. 1).

2.2.2. Test boxes

Eighteen wooden test boxes 18 cm wide, 15 cm high and 20 cm deep) were constructed for the experiment. Each box (Fig. 2) contained two heating plates, a temperature sensor and supports for the test surfaces. A speed-controlled fan mounted on the underside of the top heating plate, inside the box, equalised the temperature inside. An optimal state estimator controller based on actual temperature measurements and a physical model of the system, controlled the inside temperature. The actual temperature was measured with a custom-built TSYS01 temperature sensor board. TSYS01 temperature sensors (Model: CDE50383T) are factory-calibrated digital single chip sensors with an accuracy of ± 0.1 °C and resolution of ± 0.01 °C. Each box was equipped with

Fig. 1. Test surfaces. (From left to right: pinewood oakwood, ceramic tile).

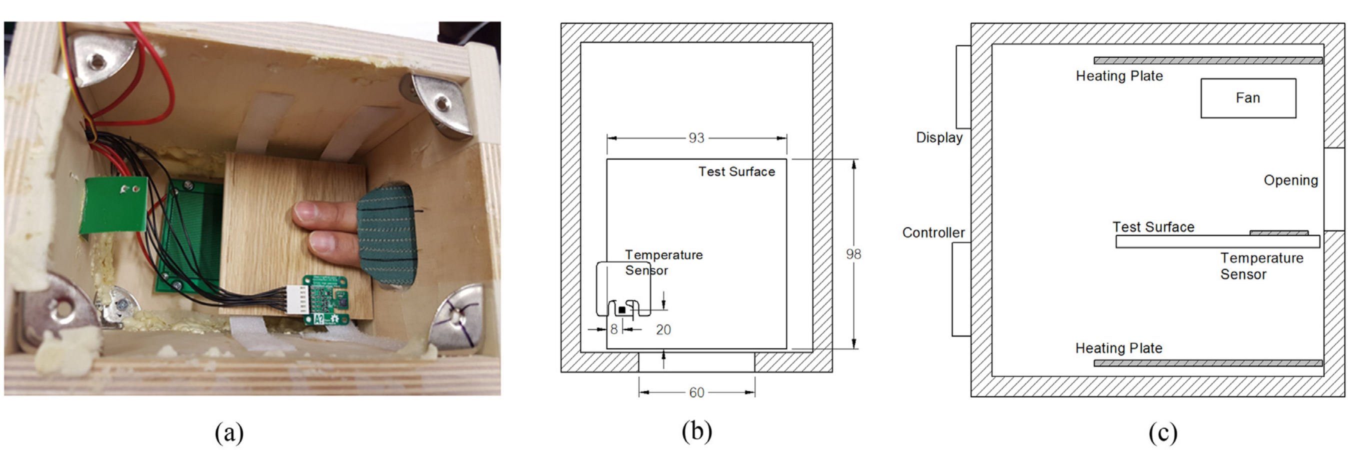

Fig. 2. 2a. The test box with the cover removed. Finger guards (not shown in the image) were used to cover the upper skin of the fingers during the test. **2b**. Schematic diagram of the box. The measurement unit is millimetre (mm) **2c**. Cross-sectional diagram of test box.

Fig. 3. The stabiliser.

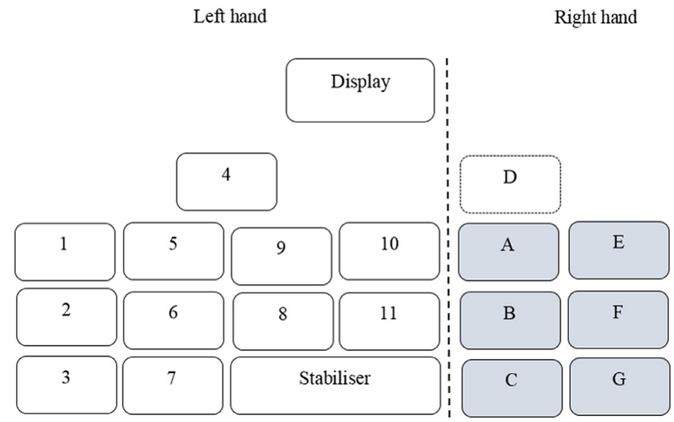

Fig. 4. Setup of the test boxes. The blue/grey boxes maintained the pine surfaces at 20 ºC, and the white boxes had tile or oak surfaces at 11 different temperatures. The box D had the lowest temperature of 14 ºC, and it was used only at the beginning of each test-round together with box number 4 in which the same material (oak or tile) was at a temperature of 24 ºC. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

an Arduino Pro Mini 3V3 microcontroller board running the control program and a display unit showing the target temperature for the test surface, the current temperature of the heating plate and the current temperature of the test surface.

Each test surface was placed 3 cm above the heating plate, and the temperature sensor was attached to the surface within 1–2 cm of the contact area. On the front side of the box, there was a 4×6 cm opening where the test subject could insert two fingers (index and middle fingers) to touch the test surfaces during the experiment. A curtain was placed over the opening to block vision and to control the airflow. The upper skin of the test fingers was covered with a finger-guard to avoid the direct air flow from the fan.

A custom-made device (40.5 cm length $\times$ 20 cm breadth $\times$ 21 cm height) was used to stabilise the hand-skin temperature at 33 ± 0.5 °C during the experiment (Fig. 3). Inside the device, a copper plate was placed above a heating element to provide comfortable touch and a uniform temperature over the surfaces of the hands. The front side of the device had two openings (6×10 cm) where the test subject could put his/her hands before and after touching the test surfaces. Curtains from soft cloth were placed over the openings.

2.2.3. Test-setup

The test boxes were arranged as shown in Fig. 4. On the left side there were 11 boxes that were easily accessible with the left hand and the other seven boxes were accessible to the right hand. The eleven boxes on the left had either the oak (series 1) or ceramic tile samples (series 2) installed, and the other seven boxes on the right contained pine samples. A computer-display was placed in front of the participant, and the boxes were coded 1 to 11 on the left and from A to G on the right. The test samples in the boxes were heated according to the plan shown in Table 2. The hand temperature stabiliser was placed at waist-level, just below the test boxes so that it was accessible to both hands and comfortable when both hands were kept inside.

2.3. Procedure

The participants wiped their hand with wet paper wipes and dried them with a cotton towel prior to participating in the experiment. They were asked to be seated comfortably in front of the setup and wear noise-cancelling headphones. The participants received proper instruction and practice before the test itself, and it took twenty minutes to acclimatise to the procedure. During a trial, the participants were guided by a computer display to find the correct pair of boxes into which they simultaneously inserted the index and middle fingers from each hand in the boxes. The participants were instructed to touch the test surface in static mode. They followed an audio signal of 7 s interval for the surface touch and 15 s for the hand warming. Seven seconds were allowed for touching the test surfaces, but the actual time for skin-to-surface contact was only 3 to 4 s because 3–4 s were spent in moving the hands from the stabiliser to the test boxes. At the end of the trial, the participants chose the surface that felt colder. The hands were simultaneously withdrawn from the test boxes and inserted back into the stabiliser. There were 11 trials in each run and eight runs were conducted for each participant. An additional trial of 24–14 °C temperature combination (box combination, 4-D) was performed for stimulation before each run, but was not recorded. Within each run of the 11 trials, the order of trials were randomised. There was a break of at least 2 min after each run and the participants were asked to wipe their hands during each break. They did not know about the types of material used in the experiment and no feedback about their judgment was given during the experiments. The touch pressure was not controlled, but the participants had the opportunity to practice applying a uniform pressure before the test session began. The participants' responses were recorded using pencil on paper. It took 30 to 40 min to complete the main task.

2.4. Data analysis

The cumulative percentages of correct responses in the trials were calculated for each participant and for each group in the two sessions. A cumulative (Gaussian) distribution function was fitted using minimised squared error to the best-fit model for the

Table 2
Temperature distribution of tile and oak surfaces in boxes 1–11.

Temperature	16	16.8	17.6	18.4	19.2	20	20.8	21.6	22.4	23.2	24	24.8	25.6
Oak box ID	8	1	5	3	10	2	7	9	6	11	4		
Tile box ID			8	5	10	2	7	9	6	11	4	1	3

observed data. The model-fit from the observed data was used to obtain the 50% response level, defined as the point of subjective equality (the PSE) in cold sensation. The 25% and 75% response levels were chosen as threshold points indicating that participants could reliably discriminate (the DT) the surface being felt as colder or warmer, respectively, from the temperature of the surfaces at the PSE.

3. Results

3.1. The PSE and the DT in pine/oak comparison

In Fig. 5, each red circle shows the observed data points from group-level data in the pine/oak comparison. From the model-fit (continuous dashed red curve), the 50% response level indicates the PSE, at which point the physical temperatures of the pine and oak surfaces evoke an equal temperature sensation. The model-fit thus shows that the pine surface, when at a physical temperature of 20 °C felt equal in temperature to that of the oak surface when the latter was at a physical temperature of 20.9 °C. This implies that an oak surface needs to be at a temperature 0.9 °C higher than a pine surface (at 20 °C) in order for both surfaces to be perceived equal in tactile cold sensation.

DT is the temperature difference at which the temperatures of pine and oak can be reliably discriminated. It is expressed as the temperature difference (in degrees Celsius) above and below the PSE (shown as the blue shaded area in Fig. 5) and in this case was found to be 1.2 °C. This means that oak is perceived to be warmer than pine when its temperature is 1.2 °C higher than the PSE (20.9 °C); i.e. at 22.1 °C. This also means that oak is perceived to be colder than pine when its temperature is 1.2 °C lower than the PSE, in other words when the temperature is 19.7 °C. When comparing these temperatures with the standard 20 °C temperature of pine, it means that as soon as the temperature of oak decreases below that of pine, it feels colder (to be exact, by at least 0.3 °C colder). Also, this means that the temperature of oak needs to be increased above that of pine by at least 2.1 °C (i.e. to 22.1 °C) before it feels warmer. The range of temperatures at which an observer is unable to discriminate reliably between the pine and oak surfaces based on the tactile cold sensation is thus quite large at 2.4 °C (19.7–22.1 °C – the “window of equality”).

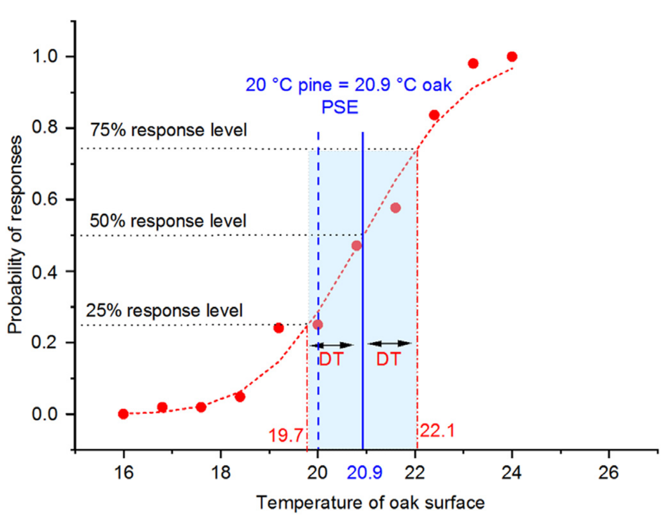

Fig. 5. The PSE and DT in pine/oak comparison. The x-axis shows the oak surface temperature, and the Y-axis shows the probability of “colder” responses to pine. Each circle denotes the observed data points, and the dashed red curve shows the model-fit.

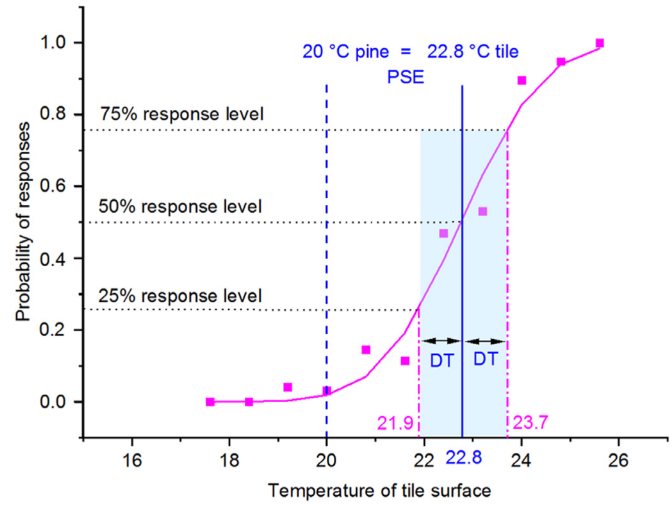

Fig. 6. The PSE and DT in pine/tile comparison. The x-axis shows the tile surface temperature, and the Y-axis shows the probability of “colder” responses to pine. Each square indicates the observed data point, and the continuous line shows the model-fit.

3.2. The PSE and the DT in pine/tile comparison

As shown in Fig. 6, when the temperature of the tile surface was at 22.8 °C, it felt equally cold (the PSE) to that of the pine surface when at a temperature of 20 °C. At the PSE, therefore, the actual difference in the physical temperature of the pine and tile was 2.8 °C. In this case, the DT was found to be 0.9 °C, meaning that on further warming of the tile surface from the PSE (22.8 °C) to 23.7 °C, tile began to feel warmer. Similarly, decreasing the temperature of the tile surface from the PSE (22.8 °C) to 21.9 °C, the tile began to feel colder. When comparing these threshold points (i.e. 23.7 °C and 21.9 °C) with the baseline pine surface at 20 °C, it means that the tile surface always felt colder than the pine when both surfaces were at 20 °C. Indeed, in the pair, the tile felt colder even when its surface temperature was increased to 21.9 °C. Also, the temperature of the tile needed to be increased above that of pine by at least 3.7 °C before the tile started to feel reliably warmer.

Table 3 shows the temperature of the comparison surfaces at the PSE, and the DT obtained from the model-fits using individual-level data. These show rather consistent values in temperature perception.

4. Discussion

The aim of the present study was to quantify the perceived similarities and differences in the temperature sensation felt between pine and either oak or ceramic tile surfaces, by measuring the point of subjective equality and the discrimination threshold in psychophysical tests, whilst ensuring that the hand temperature remained constant when in contact with the surfaces. The surface temperatures of pine and oak were found to be closer to one another at the PSE than pine and ceramic tile. In other words, for the pine and oak surfaces to be perceived to be equally cold, the latter would have to have a higher physical temperature (in this case 20.9 °C). The same is true of the pine-ceramic tile combination – the ceramic tile needs to be at a higher temperature (22.8 °C) in order to feel equally cold as pine. The fact that the temperature of the ceramic tile needs to be almost 2 °C warmer than oak at the PSE points strongly towards differences in the physical properties of the materials being the underlying cause of this phenomenon. It is also noteworthy that the DT in the pine-oak comparison was found to be greater than in the pine-ceramic tile

Table 3
The temperature of comparison surfaces (oak or ceramic tiles) at the PSE and the DT when they are compared with standard pine surface temperature, 20 °C.

Pine/oak comparison			Pine/tile comparison	
Participant	Temperature (ºC) of oak surface at the PSE	DT (ºC)	Temperature of tile surface at the PSE	DT (ºC)
1	21.0	1.1	22.5	0.8
2	21.0	1.4	22.7	0.8
3	20.8	1.3	23.5	0.8
4	20.9	1.2	22.7	0.9
5	20.6	0.8	23.4	1.0
6	21.2	1.0	22.7	0.9
7	20.5	1.4	22.2	1.3
8	20.7	1.3	22.9	0.8
9	21.3	1.2	22.7	0.9
10	21.3	0.9	22.7	1.1
11	20.9	1.2	22.3	0.9
12	21.2	1.3	22.8	0.8

*NB: The participants in the experiments were different for the pine-oak and pine-tile comparisons.

comparison, seeming to suggest that differences in the physical properties may be a significant contributory factor.

At the PSE, the temperature of the pine surface was lower than that of both the oak and the ceramic tile surfaces. To our knowledge, no research has thus far measured the PSE in cold sensation using stimuli from two different materials having different thermal properties, so here we offer possible explanations for the differences in the surface temperatures observed. When the materials being evaluated are at the same temperature and have the same thermal properties, objective equality is expected, i.e. the coldness of two surfaces is perceived to be similar in magnitude when their temperatures are equal. In the current case, however, we have dissimilar materials with different thermal properties. As noted earlier, materials with higher effusivity (oak and ceramic tile in this instance), will ‘extract’ heat from the skin at a faster rate upon contact than materials, such as pine, with lower effusivity [10,3,18]. Because at the PSE an equal intensity of cold sensation is felt on both surfaces, it is plausible that the heat flux between the skin of the fingers of each hand and the surfaces being touched are the same. A similar amount of heat extraction from dissimilar materials can only occur if there are differences in the surface temperatures. Thus, the material with a higher effusivity (tile) has to be maintained at a higher temperature than the lower effusivity material (oak) in order to feel equally cold as pine.

The rate of skin cooling can influence the threshold for cold temperature discrimination. With faster skin cooling, DT becomes smaller, indicating greater sensitivity [16,24]. The DT in the pine-oak test was 1.2 °C, and 0.9 °C in the pine-tile comparison, suggesting that it is easier to detect differences in temperature between pine and ceramic tile than between pine and oak. The DT is the temperature difference from the PSE, established in the pine-oak and pine-ceramic tile pairing tests, where the pine surface (at 20 °C) appears to feel either colder or warmer than the other material in the pair. In the pine-oak comparison, if the surface is either warmed or cooled by 1.2 °C from the 20.9 °C PSE, the oak surface will begin to feel either warmer (when it is at 22.1 °C) or colder (when it is at 19.7 °C) than pine at 20 °C. This implies that at a room temperature of 20 °C, an oak surface will feel neither warmer nor colder than its pine counterpart. On the other hand, in the pine-tile comparison, the ceramic tile needs to be is warmed to 23.7 °C (22.8 °C + 0.9 °C) for it to feel warmer than the pine at 20 °C. At the lower threshold of 21.9 °C (22.8 °C–0.9 °C), it will begin to feel colder than the pine. So, in this case, if both surfaces are at a room temperature of 20 °C the ceramic tile will feel noticeably colder.

These findings also show that when the temperature of the oak or tile surface is maintained between the range of the lower and upper threshold, i.e. “the window of equality”, discriminating their surface temperatures from 20 °C pine is not possible. This window of equality is 2.4 °C (PSE ± 1.2 °C) between pine and oak, whereas it is only 1.8 °C (PSE ± 0.9 °C) between pine and tile. A smaller DT in a material pair means that it is easier to discriminate one material surface from the other based on tactile cold sensation.

These results are comparable with previous findings about material discrimination based on thermal touch where larger differences in thermal properties are considered to be a pre-requisite for discriminating one from another [13,14,11,3,12]. With a larger difference in the thermal properties between two materials, material discrimination becomes easier when both materials are at the same temperature. In the present study this is reflected by a smaller DT in the sensory discrimination task.

Wood materials feel relatively warmer than many other building materials at room temperature and variation between wood from different tree species is often detectable in subjective rating studies and as well as in judgements from panellists (e.g., [20]). However, such subjective assessments may be biased and may not be very accurate when drawing conclusions about the tactile warmth of building materials. A psychophysical approach to thermal touch quantification can assess the perception of a material’s surface temperature in a less biased way and provide accurate numerical values to the subjective experiences that are based solely on sensory thermal cues. The ability to quantify temperature sensation in this way, by combining the measurement of subjective thermal perception with ‘hard’ physical properties, might enable the development of new ways of designing material surfaces in a systematic manner that augment the thermal comfort of users.

Using PSE and the DT as measures of the thermal behaviour of building materials could provide an insight into how to evaluate energy performance in the built environment. PSE indicates a psychological state where two different materials are perceived to be equal in tactile coldness, and hints at the possibility of creating two environments that are equal in terms of thermal comfort, but are at two different temperatures. Of course, the choice of a lower material temperature would certainly be the energy-efficient option, all other things being equal. Similarly, the DT could serve as a demarcation point, from where changes in the perception of cold or warmth emerge. Considering the use of warm materials, keeping the material temperature below the threshold in the living spaces may not change the comfort level of inhabitants but is likely to influence the use of space-heating energy. Therefore, increasing the use of warm materials in living spaces could be a passive way to reduce the energy demand for space heating in buildings. Further research is needed to elaborate on this preliminary idea and, perhaps, develop modelling to predict the energy required for space heating in the building due to the use of certain construction materials. Nevertheless, the concept of thermal touch quantification seems to be an excellent way of comparing the tactile warmth and thermal behaviour of building materials in numerical terms.

5. Conclusion

We quantified the perceived similarities and the smallest detectable differences in thermal sensation evoked between the surfaces of pine wood, oak wood, and ceramic tile using two psychophysical concepts: the point of subjective equality and the discrimination threshold. Regarding PSE, for it to feel thermally equal to a pine surface, an oak surface had to have a slightly higher temperature, meanwhile a tile surface had to have a much higher temperature than a pine surface. This most likely reflects the magnitude of the differences in physical properties between the surfaces. On the other hand, tactile discrimination of temperatures was better between dissimilar materials, as indicated by smaller values of DT between pine and ceramic tile surfaces than between pine and oak. The present study quantifies how much colder a ceramic tile surface feels than pine surface at room temperature. The methodology used here should be useful for precisely assessing the subjective experiences of the thermal quality of building materials. The quantification of temperature sensation seems promising for diverse applications including material selection, and an evaluation of the tactile warmth and thermal behaviour of materials used in living spaces.

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The details of the parts used and user instructions for the heating board's assembly can be found here https://github.com/Ell-i/ELL-i-KiCAD-Boards/tree/master/TSYS01.

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Author contributions

All the authors contributed to the conception of the work and writing the manuscript. SB collected data, SB and KT analysed the data.

Conflicts of interests

The authors declare no conflicts of interests.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.04.047.

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